

# Soil quality index as a tool for Scots pine (*Pinus sylvestris*) monoculture conversion planning on afforested, reclaimed mine land

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**Abstract:** In Central Europe, a large portion of post-mining sites were afforested with Scots pine, which is characterized by good adaptability and a tolerance for poor habitat at the beginning of forest ecosystem development. Conversion of monoculture on mine sites into more biodiverse mixed hardwood forests, especially on more fertile deposits, can be an emerging need in this part of Europe in next decades. The ability to classify the forests at these post-mining sites will facilitate proper species selection as well as the management and formation of the developed ecosystem's stability. This work describes the guidelines that can be followed to assess reclaimed mine soil (RMS) quality, using the mine soil quality index (MSQI) and a classification of developed forest sites as a basis of tree-stand species selection and conversion of pine monocultures. The research was conducted on four post-mining facilities (lignite, hard coal, sulphur, and sand pit mining areas) on different RMS substrates dominant in Central Europe. Soil quality assessment takes into account the following features of the soil: texture soil nutrients (Ca, Mg, K, Na, P); acidity (pH KCl); and  $C_{org}$ -to- $N_i$  ratio in the initial organic horizon. An analysis was conducted of classification systems using the MSQI validation correlation (at  $p = 0.05$ ) with vegetation features affected by succession: aboveground biomass of forest floor and ecological indicators of vascular plants (calculated on the basis of Ellenberg's (2009) system). Eventually, in the analysed data set, the MSQI ranged from 0.270 for soils on quaternary sands to 0.720 for a mix of quaternary loamy sands with neogene clays. Potential forest habitat types and the

role of the pine in the next generation of tree stands on different RMS parent rock substrate were proposed.

**Keywords:** mining sites, afforestation, pine monoculture conversion, soil quality index, forest habitat classification.

## Introduction

Different components of mining activities including exploration, extraction, and processing impose extensive physical, chemical, and biological changes on the environment due to the nature and characteristics of the activities (Daniels and Stewart 2000; Hüttel and Weber 2001; Machaina 2001; Pietrzykowski and Krzaklewski 2007).

Correct identification of habitat conditions at mining sites and planning species composition in afforestation both have a fundamental impact on the stability of reclaimed stands and developed forest ecosystems (Gale et al. 1991; Heinsdorf 1996; Burger and Kelting 1999; Knoche et al. 2002; Krzaklewski and Pietrzykowski 2007). Diagnosis and classification of habitats on mining soils reclaimed for forestry is of paramount importance for a proper selection of species composition in afforested sites. Proper selection of tree species means their ecological requirements are appropriately adjusted to habitat conditions (climate conditions, fertility and soil humidity).

In Central Europe, a huge area of reclaimed post-mining sites, especially the Lusatia Mine District in Germany and in Central Poland, were afforested with a pine monoculture (Heinsdorf 1996; Knoche 2005; Baumann et al. 2006; Pietrzykowski 2010). This forest management and afforestation practice is based on the assumption that the initial habitats should follow primary succession and, during the first stage, the biotope is colonized by pioneers.

The Scots pine (*Pinus sylvestris* L.) is a very useful for reclamation and afforestation on post-mining sites due to its adaptability and tolerance of poor habitat (Knoche 2005; Baumann et al. 2006; Pietrzykowski and Socha 2011). This species is native to Europe and Asia, ranging from Great Britain and Portugal in the west, Eastern Siberia in the east, the Caucasus Mountains in the

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south and as far north as well inside the Arctic Circle in Scandinavia (Farjon 2005). In the case of post-mining sites with more fertile deposits, there is a movement toward converting single-layered Scots pine monocultures into mixed hardwood forests for increasing biodiversity, tree-stands resistant to damage caused by insects and fungi gradations and better habitats utility for hardwood species. Generally, the transformation of Scots pine monoculture on potentially fertile soils into close-to-nature mixed hardwood forests stands with deciduous species is an important forestry practice in Europe in last decades (Buczko et al. 2002). This practice accelerates better equilibrium between litter production and decomposition and eventually the distribution of humus stock in the organic layers and the mineral horizon (Fischer et al. 2002).

In the case of developed ecosystems on post-mining sites, the most important issue is their biodiversity and stability, which are characteristic of mixed forests. Habitat classification is the basis for species selection and stand composition in forestry. In the case of post-mining sites afforested with pioneer species like the Scots pine, the soil quality index would be a good tool for planning monoculture conversion to mixed forests in the next generation of tree stands.

When planning the reconstruction of species composition the best time to start is at the first generation stand, when the assessment of habitat conditions forming under dynamic ecosystem succession is possible (Knoche 2005). Carrying out soil quality assessments with regard to tree species selection before establishing the first forest stands on mining sites will also pay off in the long run (Pietrzykowski 2010).

Methods of habitat productivity assessment, developed for “natural” forests are of little use in the classification of habitats on mining soils reclaimed for forestry (Pietrzykowski and Socha 2011). Mining and tipping result in the mixing of deposits differing in (Quaternary, Neogene, Carboniferous strata). This affects in diversity of soil texture (mixing sand, clay, silt), and in many other parameters (pH, soil fertility and nutrient status, trace elements, air-water properties) compare to “natural” soils. Thus the newly formed habitats are completely different from “natural” habitats.

The newly-formed soils are characterized by highly changeable chemical and physical properties and the consequential large spatial variability in habitat conditions. Characteristic features of reclaimed mine soils (RMS) include: lack of soil organic matter (SOM), nutrient deficiency (mainly of nitrogen and phosphorus); low pH-values due to acid mine drainage; unfavourable air-water properties; and salinity (Daniels et al. 1992; Burger et al. 1994; Andrews et al. 1998; Heinsdorf 1996; Katzur and Haubold-Rosar 1996; Daniels and Stewart 2000). However, elements’ deficiency in RMS is not the only problem as there may also be excessive concentrations of sulphur from pyrite oxidation and acid mine drainage on the Neogene strata (Katzur and Haubold-Rosar 1996). These features restrict harmonious nutritive conditions for trees in recreated forest ecosystems (Burger et al. 1994; Heinsdorf 1996; Knoche 2005; Knoche et al. 2002; Pietrzykowski 2008).

An objective comparison of soil quality on the basis of quanti-

tative indices (e.g., soil quality index SQI) is important for sustainable forest management and stability of the ecosystem, which also has protective and non-productive functions (connected with aesthetics and well-being). A uniform system of soil quality assessment based on the SQI is also important for monitoring the anthropogenic impact on the environment (Schoenholtz et al. 2000) and is useful for universal assessment of potential forest soil productivity (Gale et al. 1991; Burger and Kelting 1999; Knoepp et al. 2000; Brożek et al. 2011). In practice, soil quality can be evaluated on the basis of its chemical, physical, and biological properties (Doran and Parkin 1996; Henderson 1995; Regenold and Palmer 1995; Harris et al. 1996; Nambiar 1997; Powers et al., 1998; Schoenholtz et al., 2000).

An example of SQI used on reclaimed sites is an index developed by Gale et al. (1991) for the assessment of habitat conditions for the cultivation of white spruce (*Picea glauca* (Moench) Voss.) and an index described in the work of Burger et al. (1994) developed for the assessment of habitat conditions on reclaimed sites in the Appalachian Mountains for the cultivation of pine (*Pinus virginiana* Mill).

In this work, the Mine Soil Quality Index (MSQI) was proposed for the assessment of initial mining soils and classification of habitats on post-mining sites afforested with a monoculture of the Scots pine (*Pinus sylvestris* L.). The MSQI may be useful as a tool for planning species composition, both for afforestation and pine monoculture conversion in the next generation of tree stands.

## Material and methods

### Study sites

Field research was conducted on monoculture stands of the Scots pine (*Pinus sylvestris* L.), ranging from 12 to 30 years of age on the following reclaimed and afforested post-mining sites on different parent rocks (substrate), including dominant types in Central Europe (Quaternary, Neogene and Carboniferous strata). First, a total of 32 square research plots measuring 10 m × 10 m each were set up and from there, four replications × 8 RMS substrate (parent rock) variants were established on four mine sites: (1) the hilltop of an external waste heap at Bełchatów Lignite Mine; (2) a spoil heap of Smolnica hard coal mine; (3) the bottom of Szczakowa sand pit; and, 4) a waste heap of Piaseczno open-cast sulphur mine. Detailed site characteristics have been provided in Table 1.

### Soil study

As part of the soil studies soil profiles on all study plots (total 32 profiles) were exposed in pits to a depth of 110 cm. Additionally for composed soil sample preparation an extra 5 bore holes were made on each plot with a soil auger (Eijkelkamp set) on a grid. These composed soil samples were taken (1.0 kg mass of sample) to determine basic soil properties at depths of 0–8 cm (Ai – initial organic-mineral horizons); 8–50 cm and 50–110 cm (C –

parent materials/rocky spoils). Independently, soil bulk density (BD) was sampled by the core method, using standard sharpened steel cylinders (250 cm<sup>3</sup>) (according to procedures in De Vos et al. 2005) with 3 replications for each layer (0–8; 8–50 and 50–110 cm deep) in the RMS pits (one soil pit for each soil-

substrate variant). In the lab, soil samples were dried and brushed through a 2.0 mm sieve. Samples of organic horizons OLF (annotated with FAO syntax where L = leaf; f = fermentation/fragmentation humus layers) were collected after litterfall from 1 m × 1 m quadrates with 3 replications for each 100 m<sup>2</sup>.

**Table 1.** Site characteristics

Feature	Bełchatów spoil heap (BEL)	Smolnica spoil heap (SMOL)	Szczakowa sand pit (SCZ)	Piaseczno spoil heap (PIAS)
Location (GPS)	N51 13.196 E19 25.569	N50 15.078 E18 31.021	N50 14.880 E19 23.932	N50 33.622 E21 34.185
Elevation (m.a.s.l.)	350	226	282	197
Mean annual precipitation (mm)	580	702	700	650
Mean annual temperature (°C)	7.6	7.7	8.0	7.0
Parent material (substrate)	<b>BEL-QL:</b> Quaternary loamy sands, loam, bouldery clay;	<b>SMOL-CF and SMOL-NFC:</b> Carboniferous deposits: mudstones, sandstones and carbonaceous shales	<b>SCZ-QS:</b> fluvioglacial Quaternary sands;	<b>PIAS-QS+NC:</b> a mixture of Quaternary sands and Neogene Krakowice Beds formation clays;
	<b>BEL-NS:</b> Neogene sands with loam, carbonated and sulphurised		<b>SCZ-QLS:</b> fluvioglacial Quaternary loamy sands	<b>PIAS-QLS:</b> Quaternary loose sands
Reclamation and reforestation treatments	<b>BEL-QL</b>	<b>SMOL-CF</b>	<b>SMOL-NFC</b>	<b>SCZ-QLS and SCZ-QS</b>
	fertilization (60 kg N, 70 kg P, 60 kg K ha <sup>-1</sup> ); sowing grasses and leguminous (60 kg ha <sup>-1</sup> ); planting of pine trees.	fertilization (100 kg N, 20 kg P, 20 kg K ha <sup>-1</sup> ); self-sown seedlings of pine.	unfertilized substrates, self-sown seedlings of pine.	organic amendment addition (300 m <sup>3</sup> ha <sup>-1</sup> organic horizons from forest soil, approx. 1.0 % C <sub>org</sub> content); liming (1.5 Mg dolomite ha <sup>-1</sup> ); fertilization (140 kg N, 130 kg P, 150 kg K ha <sup>-1</sup> ); 2-years legume cultivation (240 kg ha <sup>-1</sup> ); planting of pine trees.
Pine tree stand age (years)	<b>BEL-NS</b>			<b>PIAS-QS+NC and PIAS-QLS</b>
	fertilization and afforestation as in the case of BEL-QL + neutralisation with bog lime (60 Mg ha <sup>-1</sup> ).			fertilisation (80 kg N, 50 kg P, 60 kg K ha <sup>-1</sup> ); 2-years white legume cultivation (sowing 200 kg ha <sup>-1</sup> ); planting of pine trees.
	17	12	30	30
				21
				23
				30

Next, mixed samples of organic horizon for each plot were prepared for laboratory testing. The basic soil parameters were determined in the samples using laboratory procedures:

- particle size distribution was determined by hydrometer analysis and sand fractions by sieving;
- the pH of the soil was measured with a combination electrode in suspensions of 1.0 mol L<sup>-1</sup> KCl (pH<sub>KCl</sub>) (1:2.5 mass/volume ratio) after 24 hour equilibration;
- organic soil carbon (C<sub>org</sub>) and total nitrogen (N<sub>t</sub>) were assayed with a Leco CNS 2000 Elemental Analyzer; and
- basic exchangeable cations (Na<sup>+</sup>, K<sup>+</sup>, Ca<sup>2+</sup>, Mg<sup>2+</sup>) were extracted with 1 mol L<sup>-1</sup> NH<sub>4</sub>OAc.

Samples were then mixed with a small portion of extractant and equilibrated. After 24 hours, the suspensions were filtered, the soils were washed with additional extractant, and the total volume was made up to 100 mL (Jackson, 1958). The concentration of cations was determined by atomic absorption spectroscopy (AAS) with a Varian Spectrophotometer. Phosphorus in the form available to plants (P<sub>av</sub>) was assayed using the Egner-Riehm method in calcium lactate extract ((CH<sub>3</sub>CHOHCOO)<sub>2</sub>Ca) acidified with hydrochloric acid to pH 3.6 and using the colori-

metric method (Ostrowska et al. 1991) with VARIAN Inc., Cary 300 UV-Vis Spectrophotometers.

#### Plant community studies

Vegetation coverage on the study plots was determined using the Braun-Blanquette method (100 m<sup>2</sup> phytosociological surveys on each experimental plot, total of 32) (Wikum and Shanholtzer 1978). Next, ecological indicators of moisture (M) and fertility (F) for the forest floor species composition were calculated based on ecological numbers of vascular plants in Europe (Ellenberg 2009). In the analyzed cases, an 5-grade scale was used where the intensity of particular factors increases from (0) 1 to 5 (6) (Zarzycki et al. 2002).

As is widely known many plant species are good indicators of habitat conditions. Detailed studies conducted 60 years ago allowed to calibrate many plant species with reference to habitat conditions; Ecological indicator values for Central Europe (Ellenberg 2009) have been used successfully by many authors (Dzwonko 2001). In most cases, a 5-grade scale was used where the intensity of particular factors increases from (0) 1 to 5 (6)

(Zarzycki et al. 2002). Here, to calculate the values of the given indices, the species abundance index according the Braun-Blanquette scale was converted into numerical values: cover above 75% corresponds to "5", cover range from 50%–75% to "4", 25%–50% to "3"; very abundant or 5%–25% to "2"; numerous individuals but not abundant to "1"; rare and not abundant to "0.5"; few individuals to "0.2" and very rare (one) corresponds to "0.1". Calculations were made as a weighted average of ecological indicator values, first for an individual phytosociological survey on each plot and later for mean values for substrate type (variants) on the sites.

Forest floor vegetation biomass was determined using the harvest method on 96 sample sub-plots ( $1 \text{ m}^2 \times 3$  replications distributed along the diagonal of each of 32 soil study plots measured  $10 \text{ m} \times 10 \text{ m}$ ) in the middle of the vegetation season (July). Mixed samples of vegetation (aboveground biomass of herbaceous and shrubs, Biom H+S) were collected to determine the water content (%) and calculate dry mass in the laboratory.

### Statistical procedures

Data were analyzed with Statistica 9.1 software (StatSoft Inc. Software, 2009). Significant differences between the mean values of basic soil characteristics and MSQI from differing groups of soil-substrate (parent rock) variants were tested by an ANOVA test, preceded by a Shapiro-Wilk test of normality, and Levene's test of variance homogeneity. The ANOVA test was followed by multiple pairwise comparisons using Tukey's HSD (honestly significant difference) post-hoc test. Based on the results of Tukey's HSD test homogeneous subsets in terms of index values MSQI were distinguished. Correlation analysis between MSQI and plant features for the validation model was performed using the Pearson's correlation coefficient  $r$  (at the significance level  $p=0.05$ ).

### The development and calculation of mine soil quality index (MSQI)

Following the studies and concepts presented by Gale et al. (1991), Burger and Kelting (1999), Brożek et al. (2011) some assumptions were made to develop the MSQI index. The components of the soil assessment index include basic soil properties contributing to its fertility such as soil texture, nutrient availability, acidity converted into volumetric units, and sub-indices. Furthermore, each of the sub-indices was weighted with consideration of its estimated impact on the final assessment and standardised according to absolute values ranging from 0.0 to 1.0. Each feature was standardised using a linear function, taking into account three approaches: first, more (increase in feature value) is worse; second, more of a given index is better for the plant; third, at first more is better, then there is an optimum, and further increase is worse.

MSQI takes account of the following features (Table 2): the stock of soil texture fractions; nutrient availability, acidity (pH) and biological activity (expressed by  $C_{\text{org-to-N}_t}$  ratio). The value of each feature was first defined for particular horizons, i.e.: 0–8

cm (organic mineral initial horizons Ai); 8–50 cm (parent rock C horizon, a layer most intensively penetrated by tree root systems in mine soils); and 50–110 cm (parent rock C horizon, approximate root range). The index referring indirectly to the decay rate of precipitate in the form of organic matter and soil biological activity (i.e., the  $C_{\text{org-to-N}_t}$  ratio), was defined only for the forest litter and partially decomposed humus layers (OLf).

The developed MSQI index is the sum of sub-indices weighted with a relevant validity coefficient factor ( $wt$ ) provided for a given feature, where the maximum value of 1.0 corresponds to 100%.

Finally, a general equation was applied to calculate the MSQI (Equation 1):

$$\text{MSQI} = (\text{Ist } wt(0.3)) + (\text{Ina } wt(0.3)) + (\text{IP } wt(0.1)) + (\text{Iac } wt(0.2)) + (\text{Iba } wt(0.1)) \quad (1)$$

where:

$wt$  is weight as a validity coefficient factor for individual sub-index; **Ist** is sub-index of soil texture, which is the sum of **Isi**, the silt sized fraction stock (SFS, 0.05–0.002-mm fraction) and **Icl**, the clay sized fraction stock (CFr, <0.002-mm fraction) calculated according to the total stock of these fractions in soil up to 110 cm profile deep ( $\text{Mg} \cdot \text{ha}^{-1} \cdot 110\text{-cm}^{-1}$ ). However, the value of this sub-index is reduced by the **Is** skeletal sub-index defined according to the % of coarse fragment (CFr, >2.0 mm) components (Equation 2):

$$\text{Ist} = (\text{Isi} + \text{Icl}) - \text{Is} \quad (2)$$

however, **Ist**  $\geq 0$  because with extreme values (small share of silt and clay sized fraction with very high coarse fragment CFr share, i.e., > 35 %) the Ist sub-index would be negative and so in such cases Ist is assumed to be 0.0,  $wt = 0.3$ ;

**Ina** – nutrient availability index refers to the nutrient content in soil volume (ECS, exchangeable cation form stock  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$ ,  $\text{Na}^+$  up to 110 cm soil profile deep),  $wt = 0.3$ ; **IP** – available phosphorus sub-index based on Available Phosphorus Stock (APS) in soil volume ( $\text{Mg} \cdot \text{ha}^{-1} \cdot 110\text{-cm}^{-1}$ ),  $wt = 0.1$ ; **Iac** – acidity sub-index based on hydrogen stock ( $\text{H}^+ \text{S}$ ) in soil volume (in units in  $\text{kg} \cdot \text{ha}^{-1} \cdot 110\text{-cm}^{-1}$ ); however  $\text{H}^+ \text{S}$  has been calculated based on  $\text{pH}_{\text{KCl}}$ , which constitutes a measure of hydrogen ions in soil water solution ratio 1:2.5. Such a manner of determining acidity allowed the researchers to avoid taking the arithmetic mean of pH from soil horizons (pH is a logarithmic value);  $wt = 0.2$ ; **Iba** – soil biological activity index based on  $C_{\text{org-to-N}_t}$  ratio in OLf horizon,  $wt = 0.1$ ;

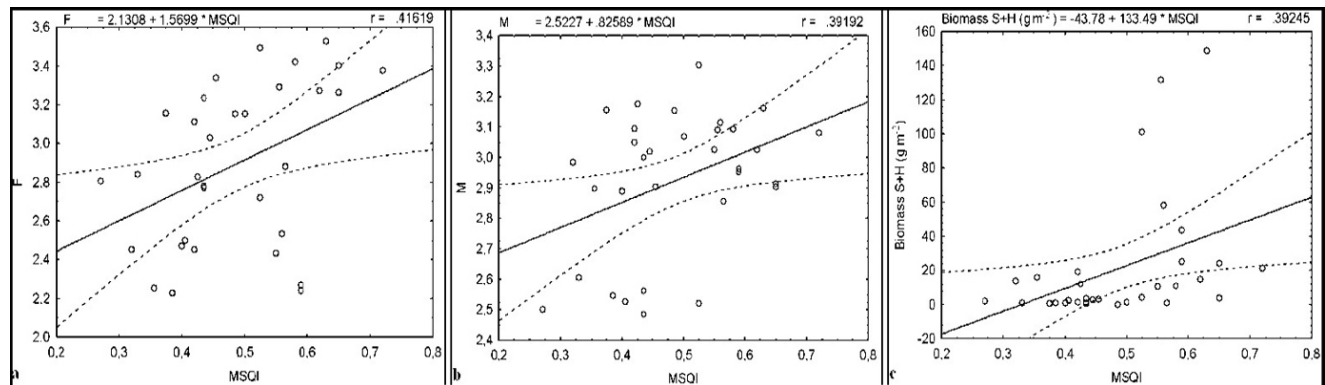
To automate the calculation of MSQI based on a scale of valuation, the *IF* function was used to perform logic tests on values and formulas in an Excel MS Office (2007) spreadsheet.

Evaluation of individual MSQI variants at different  $wt$  for sub-indices was validated by the best correlations with plant community characteristics affected by natural succession, including aboveground biomass of forest floor plant and ecological indicator of vascular plants (moisture M and fertility F). In this work, the tree stand characteristics were not considered for validation

of MSQI, because they heavily depended on the age of trees, which varied from 12 to 30 years at the post-mining site (Table 1).

The best results (at a significance level of  $p=0.05$ ) were at “wt” value respectively: 0.3 for Ist and Ina, 0.2 for Iac, and 0.1 for IP and Iba. In this case, the values of MSQI correlated sig-

nificantly with the ecological indicators: moisture (M) ( $r=0.39$ ) and fertility (F) ( $r=0.42$ ) (Fig. 1 a, b). The values of MSQI correlated significantly (at  $p=0.05$ ), as well, with aboveground biomass of forest floor species (herbaceous and shrub vegetation, Biom H+S,  $r=0.39$ ) (Fig. 1, c).



**Fig. 1.** Correlations between mine soil quality index MSQI and ecological indicators of Fertility F (a), Moisture M (b) and aboveground forest floor species community biomass (herbaceous and shrub vegetation Biom H+S) (c) in a validation model. According to Pearson's test with  $n=32$ , at  $p=0.05$  the statistical correlation at  $0.3 < r_{xy} < 0.5$  is average.

**Table 2.** Scale and list of individual partial index ranges which constitute the mine soil quality evaluation according to MSQI formula.

Group of soil properties and sub-indices of MSQI													
Texture - stock of particle size fractions: Ist = (Isi + Icl) – Is				Nutrient stock				Acidity		Biological activity			
SFS <sup>1</sup> (0.05–0.002 mm) Mg·ha <sup>-1</sup> ·110·cm <sup>-1</sup>	Isi	CIFS (<0.002 mm) Mg·ha <sup>-1</sup> ·110·cm <sup>-1</sup>	Icl	CFr (>2.0 mm) %	Is	ECS Mg·ha <sup>-1</sup> ·110·cm <sup>-1</sup>	Iab	APS Mg·ha <sup>-1</sup> ·110·cm <sup>-1</sup>	IP	H <sup>+</sup> S kg·ha <sup>-1</sup> ·110·cm <sup>-1</sup>	Iac	C <sub>org</sub> -to-N <sub>t</sub>	Iba
<250	0.05	<300	0.05	<15.0	0	<5.0	0.15	<0.005	0.15	>20.0	0.2	<28.0	1
251–600	0.1	301–600	0.1	15.0–25.0	0.1	5.1–10.0	0.3	0.0051–0.0100	0.3	10.1–20.0	0.3	28.1–35.0	0.9
601–900	0.15	601–1000	0.15	26.0–35.0	0.2	10.1–15.0	0.45	0.0101–0.0200	0.45	2.1–10.0	0.4	35.1–40.0	0.6
901–1400	0.2	1001–1500	0.2	>35.0	0.3	15.1–20.0	0.6	0.0201–0.0360	0.6	1.1–2.0	0.5	40.1–50.0	0.5
1401–1600	0.25	1501–2000	0.25			20.1–35.0	0.75	0.0361–0.0600	0.75	0.5–1.0	1	50.1–60.0	0.4
1601–2500	0.3	2001–3000	0.3			35.1–50	0.9	0.0601–0.1000	0.9	0.002–0.5	0.6	60.1–70.0	0.2
2501–3700	0.35	3001–3500	0.4			>50	1	>0.1000	1	<0.002	0.3	>70.0	0.1
3701–4300	0.4	3501–4000	0.5										
4301–8500	0.45	4001–8500	0.2										
>8500	0.5	>8500	0.1										

<sup>1</sup> SFS – Silt Sized (0.05–0.002 mm) Fraction Stock; CIFS – Clay Sized (<0.002 mm) Fraction Stock; CFr – Coarse Fragments (>2.0mm); ECS – Exchangeable Cations Form Stock; APS – Available Phosphorus Stock; H<sup>+</sup>S – Hydrogen Stock;

## Results

### Plant characteristics

The mean plant ground cover abundance was varied and ranged from 2 (SCZ-QS) to 56 % (SMOL-CF); the mean number of undergrowth species of vascular plants ranged from 13 (PIAS-QLS) to 45 (SMOL-NCF). In total, 131 plant species were identified in the post-mining sites, 29 of which were classified as

forest species, 80 as ruderal and 22 as grassland, respectively. The dominant species in the communities were: *Calamagrostis epigejos*, *Cardaminopsis arenosa*, *Cirsium arvense*, *Dactylis glomerata*, *Deschampsia flexuosa*, *Festuca ovina*, *Festuca rubra*, *Hieracium pilosella*, *Poa compressa*, *Tussilago farfara*, *Vaccinium myrtillus* respectively depending on the substrate (Table 3). However, the remaining species had no clear phytosociological relation or were characteristic for various other vegetation types. The value of the ecological indicator of moisture (M) ranged from 2.60 (BEL-NS) to 3.18 (PIAS-QS+NC) and the value of the

fertility indicator (F) ranged from 2.35 (SMOL-CF) to 3.43 (PIAS-QS+NC) (Table 3). The forest floor plant aboveground

biomass (Biom H + S) ranged from 0.13 (SCZ-QS) to 0.345 (Mg·ha<sup>-2</sup>) (SMOL-CF) (Table 3).

**Table 3.** Selected plant community features

Feature of plant community		Plant ground cover abundance (%)	Number of vascular plant species (pcs.)	Dominant species <sup>1</sup>	Aboveground biomass (forest floor) (Mg·ha <sup>-1</sup> )	Moisture (M) <sup>3</sup>	Fertility (F)
The BELCHATÓW spoil heap	BEL-QL	8	37	<i>Dactylis glomerata</i> ; <i>Tussilago farfara</i> ; <i>Cirsium arvense</i> ; <i>Deschampsia flexuosa</i>	0.135 (0.091) <sup>2</sup>	2.98 (0.10) <sup>4</sup>	3.35 (0.06)
	BEL-NS	5	17	<i>Festuca rubra</i> ; <i>Hieracium pilosella</i> ; <i>Poa compressa</i>	0.033 (0.021)	2.60 (0.20)	2.83 (0.34)
The SMOLNICA spoil heap	SMOL-CF	56	30	<i>Deschampsia flexuosa</i> ; <i>Festuca ovina</i> ; <i>Vaccinium myrtillus</i>	0.345 (0.241)	3.03 (0.05)	2.35 (0.13)
	SMOL-NCF	26	45	<i>Deschampsia flexuosa</i> ; <i>Calamagrostis epigejos</i> ; <i>Festuca ovina</i>	0.153 (0.102)	3.05 (0.13)	2.53 (0.21)
The SZCZAKOWA sand pit	SCZ-QLS	4	34	<i>Deschampsia flexuosa</i> ; <i>Hieracium pilosella</i>	0.015 (0.010)	2.90 (0.22)	2.98 (0.17)
	SCZ-QS	2	22	<i>Cardaminopsis arenosa</i> ; <i>Deschampsia flexuosa</i> ; <i>Hieracium pilosella</i>	0.013 (0.011)	2.63 (0.19)	2.58 (0.29)
The PIASECZNO spoil heap	PIAS-QS+NC	34	34	<i>Solidago gigantea</i> ; <i>Festuca rubra</i> ; <i>Equisetum arvense</i>	0.170 (0.245)	3.18 (0.10)	3.43 (0.10) <sup>a</sup>
	PIAS-QLS	4	13	<i>Festuca rubra</i>	0.073 (0.062)	3.10 (0.12)	3.18 (0.05) <sup>b</sup>

<sup>1</sup> dominant species in phytosociological surveys on plots represent site variant;

<sup>2</sup> 0.135 (0.091) – mean and standard deviation of aboveground forest floor biomass (dry mass) (Mg·ha<sup>-1</sup>)

<sup>3</sup> ecological indicators of moisture (M) and fertility (F) based on Ellenberg (2009) (description in methods section);

<sup>4</sup> 2.98 (0.10) - mean and standard deviation (number of replications for phytosociological survey on plots represent site variant n = 4)

### Basic soil properties

The properties of the investigated RMS are rather varied (statistical differences of basic soil parameters are given in Table 4). The percentage of silt-sized fraction (0.05–0.002 mm) ranged from 2.0% to 36.0% and clay sized was (<0.002 mm) between 1.0 and 25.0%. Organic carbon (C<sub>org</sub>) and nitrogen N<sub>t</sub> contents in the Ai horizon (0–8 cm depth) varied from 2.3 to 166.1 g·kg<sup>-1</sup> and 0.15 to 4.04 g·kg<sup>-1</sup>, respectively and C<sub>org</sub>-to-N<sub>t</sub> ratio in the OLF horizon between 29.3 and 83.6. Soil pH in 1 M KCl ranged from 3.13 to 7.50. The samples also differed considerably in terms of their cation exchange properties. The total exchangeable bases (TEB) were from 1.20 to 27.41 cmol<sub>(c)</sub>·kg<sup>-1</sup>, cation exchangeable capacity (CEC) from 2.18 to 28.0 cmol<sub>(c)</sub>·kg<sup>-1</sup> and base saturation (BS) from 25.96 to 98.14%. The content of available phosphorus (P<sub>av</sub>) ranged from 0.10 to 2.68 g·kg<sup>-1</sup> (Table 4).

### Value of transformed soil properties for MSQI calculation

Depending on the silt fraction content in the horizons of the investigated soils, the average stock of this fraction (SFS) ranged from 343 (SCZ-QS) to over 4827 Mg·ha<sup>-1</sup>·110·cm<sup>-1</sup> (BEL-QL) (Table 5). The clay fraction stock (CIFS) in the investigated soils ranged from 263 (SCZ-QS) to 2775 Mg·ha<sup>-1</sup>·110·cm<sup>-1</sup> (SMOL-CF) of the profile (Table 5). For the investigated RMS, the mean value of Isi ranged from 0.10 to 0.45 and Icl stock ranged from

0.05 to 0.5 (Table 5). The coarse fragment fraction CFr (fragments of rocks, stones, gravel of >2.0 mm in diameter) in RMS ranged from 0.0% (in most soils) to 80.0% (SMOL-CF). Eventually the mean value of Ist index (according to equations 2) ranged from 0.20 (SCZ-QS and PIAS-QLS) to 0.60 (BEL-QL) (Table 5). Exchangeable cation form stock (ECS) include: calcium Ca<sup>2+</sup>, magnesium Mg<sup>2+</sup>, potassium K<sup>+</sup> and sodium Na<sup>+</sup> of investigated soil ranged from 2.8 (SCZ-QS) to 99.2 Mg·ha<sup>-1</sup>·110·cm<sup>-1</sup> (BEL-QL) (Table 5).

In the investigated RMS, as in most natural soils, calcium (Ca<sup>2+</sup>) was the predominant nutrient. Available phosphorus stock (APS) in the investigated mining soils ranged from 0.0025 Mg·ha<sup>-1</sup>·110·cm<sup>-1</sup> in soils forming on Carboniferous unfertilized sediments (SMOL-NCF) to 0.4800 Mg·ha<sup>-1</sup>·110·cm<sup>-1</sup> in soils forming on acidic, sulphurous neogene sands, neutralised by bog lime (BEL-NS) (Table 4). The mean value of IP in investigated RMS ranged from 0.30 (for soils in SMOL-NCF) to 1.0 (BEL-QL and BEL-NS) (Table 5).

The acidity of the investigated soils expressed by hydrogen stock in terms of volume (H<sup>+</sup> S) ranged on average from 0.0013 (BE-QL) to over 43.5250 kg·ha<sup>-1</sup>·110·cm<sup>-1</sup> (Table 5). The mean lac for investigated soil substrate ranged from 0.2 (SMOL-CF and SMOL-NCF) to 1.0 (SCZ-QLS and SCZ-QS). The mean value of C<sub>org</sub>-to-N<sub>t</sub> ratio in OLF horizons of the investigated soils ranged from 31.5 (SMOL-CF and SMOL-NCF) to 83.6 (BEL-NS) (Table 2), and Iba sub-index for investigated soils ranged respectively from 0.1 (BEL-QL and BEL-NS) to 0.9 (SMOL-CF;

SMOL-NCF; PIAS-QS+NC and PIAS-QLS) (Table 5).

**Table 4.** Basic soil characteristics

Feature	BD (g·cm <sup>-3</sup> )		Corse frag- ments (%)	Silt sized fraction (0.05–0.002 mm) (%)		Clay sized fraction (<0.002 mm) (%)		pH KCl		C <sub>org</sub> (g·kg <sup>-1</sup> )	
horizon	Ai	C	Ai, C	Ai	C	Ai	C	Ai	C	OLF	Ai
BEL-QL	1.64 <sup>a</sup> ± 0.06	1.69 <sup>a</sup> ± 0.07	0	32 <sup>b</sup> ± 11	30 <sup>a</sup> ± 8	3 <sup>a</sup> ± 3	5 <sup>a</sup> ± 4	7.36 <sup>c</sup> ± 0.19	7.50 <sup>c</sup> ± 0.12	478.5 <sup>c</sup> ± 5.5	6.1 <sup>a</sup> ± 2.8
BEL-NS	1.62 <sup>a</sup> ± 0.06	1.71 <sup>a</sup> ± 0.07	0	8 <sup>a</sup> ± 2	17 <sup>a</sup> ± 19	3 <sup>a</sup> ± 2	6 <sup>a</sup> ± 2	4.94 <sup>bc</sup> ± 1.75	4.69 <sup>b</sup> ± 1.50	407.5 <sup>a</sup> ± 53.4	2.7 <sup>a</sup> ± 0.4
SMOL-CF	1.00 <sup>a</sup> ± 0.06	1.11 <sup>a</sup> ± 0.02	70±80	36 <sup>b</sup> ± 2	33 <sup>a</sup> ± 2	24 <sup>c</sup> ± 2	25 <sup>a</sup> ± 2	3.40 <sup>ab</sup> ± 0.20	3.60 <sup>a</sup> ± 0.43	436.0 <sup>a</sup> ± 35.0	166.1 <sup>a</sup> ± 13.0
SMOL-NCF	1.07 <sup>a</sup> ± 0.12	1.04 <sup>a</sup> ± 0.04	70±80	36 <sup>b</sup> ± 2	31 <sup>a</sup> ± 4	24 <sup>c</sup> ± 2	25 <sup>a</sup> ± 2	3.40 <sup>ab</sup> ± 0.20	3.13 <sup>a</sup> ± 0.21	436.0 <sup>a</sup> ± 35.0	166.1 <sup>a</sup> ± 13.0
SCZ-QLS	1.54 <sup>a</sup> ± 0.13	1.58 <sup>a</sup> ± 0.02	0±5	8 <sup>a</sup> ± 3	12 <sup>a</sup> ± 8	4 <sup>a</sup> ± 1	5 <sup>a</sup> ± 3	4.15 <sup>ab</sup> ± 0.06	4.60 <sup>ab</sup> ± 0.17	316.6 <sup>a</sup> ± 96.2	4.6 <sup>a</sup> ± 1.3
SCZ-QS	1.63 <sup>a</sup> ± 0.06	1.52 <sup>a</sup> ± 0.11	0±5	5 <sup>a</sup> ± 1	2 <sup>a</sup> ± 1	1 <sup>a</sup> ± 1	2 <sup>a</sup> ± 1	5.91 <sup>bc</sup> ± 2.05	6.18 <sup>bc</sup> ± 1.61	333.3 <sup>a</sup> ± 72.3	2.3 <sup>a</sup> ± 1.2
PIAS-QS+NC	1.41 <sup>a</sup> ± 0.16	1.29 <sup>a</sup> ± 0.10	0±10	11 <sup>a</sup> ± 6	8 ± 4	9 <sup>b</sup> ± 2	7 <sup>a</sup> ± 2	5.56 <sup>bc</sup> ± 1.36	6.40 <sup>bc</sup> ± 0.78	297.8 <sup>ab</sup> ± 40.8	13.2 <sup>a</sup> ± 1.9
PIAS-QLS	1.53 <sup>a</sup> ± 0.06	1.62 <sup>a</sup> ± 0.01	0±5	4 <sup>a</sup> ± 2	3 ± 1	4 <sup>a</sup> ± 1	3 <sup>a</sup> ± 1	5.39 <sup>bc</sup> ± 1.60	6.28 <sup>bc</sup> ± 0.90	329.0 <sup>a</sup> ± 103.4	4.7 <sup>a</sup> ± 0.4
Feature	N <sub>i</sub> (g·kg <sup>-1</sup> )		C <sub>org</sub> -to-N <sub>i</sub>	TEB (cmol <sub>c</sub> ·kg <sup>-1</sup> )		CEC (cmol <sub>c</sub> ·kg <sup>-1</sup> )		BS%		P <sub>av</sub> (g·kg <sup>-1</sup> )	
horizon	OLF	Ai	OLF	Ai	C	Ai	C	Ai	C	Ai	C
BEL-QL	5.79 <sup>ab</sup> ± 0.32	0.53 <sup>a</sup> ± 0.03	82.8 <sup>a</sup> ± 3.8	27.41 <sup>b</sup> ± 5.68	27.18 <sup>c</sup> ± 4.16	28.00 <sup>c</sup> ± 5.68	27.68 <sup>c</sup> ± 4.23	97.86 <sup>b</sup> ± 0.42	98.14 <sup>a</sup> ± 0.14	2.68 <sup>b</sup> ± 1.62	1.55 <sup>a</sup> ± 1.20
BEL-NS	4.87 <sup>a</sup> ± 0.48	0.15 <sup>a</sup> ± 0.02	83.6 <sup>a</sup> ± 5.7	4.07 <sup>a</sup> ± 2.00	3.28 <sup>ab</sup> ± 0.97	5.69 <sup>a</sup> ± 1.39	5.49 <sup>a</sup> ± 0.85	68.81 <sup>ab</sup> ± 20.31	61.02 <sup>bc</sup> ± 22.72	1.93 <sup>b</sup> ± 0.94	2.66 <sup>a</sup> ± 0.85
SMOL-CF	13.84 <sup>c</sup> ± 0.42	4.04 <sup>a</sup> ± 0.38	31.5 <sup>a</sup> ± 2.6	5.15 <sup>a</sup> ± 1.82	10.62 <sup>b</sup> ± 2.74	19.40 <sup>bc</sup> ± 6.49	21.30 <sup>bc</sup> ± 2.95	28.37 <sup>a</sup> ± 13.12	47.05 <sup>ab</sup> ± 10.39	0.18 <sup>a</sup> ± 0.16	0.21 <sup>a</sup> ± 0.22
SMOL-NCF	13.84 <sup>c</sup> ± 0.42	4.04 <sup>a</sup> ± 0.38	31.5 <sup>a</sup> ± 2.6	5.15 <sup>a</sup> ± 1.82	4.53 <sup>ab</sup> ± 1.67	19.40 <sup>bc</sup> ± 6.49	16.24 <sup>b</sup> ± 4.69	28.37 <sup>a</sup> ± 13.12	25.96 <sup>a</sup> ± 4.91	0.18 <sup>a</sup> ± 0.16	0.21 <sup>a</sup> ± 0.22
SCZ-QLS	7.70 <sup>b</sup> ± 2.15	0.40 <sup>a</sup> ± 0.06	41.0 <sup>a</sup> ± 5.2	1.20 <sup>a</sup> ± 0.37	2.10 <sup>a</sup> ± 0.32	2.21 <sup>a</sup> ± 0.72	3.13 <sup>a</sup> ± 0.49	56.68 <sup>ab</sup> ± 18.81	66.72 <sup>bc</sup> ± 8.06	0.12 <sup>a</sup> ± 0.03	0.11 <sup>a</sup> ± 0.03
SCZ-QS	7.83 <sup>b</sup> ± 1.75	0.30 <sup>a</sup> ± 0.09	42.8 <sup>a</sup> ± 5.1	2.59 <sup>a</sup> ± 2.72	1.28 <sup>a</sup> ± 0.92	3.68 <sup>a</sup> ± 2.44	2.18 <sup>a</sup> ± 1.11	52.05 <sup>ab</sup> ± 38.49	49.63 <sup>ab</sup> ± 12.12	0.24 <sup>a</sup> ± 0.21	0.10 <sup>a</sup> ± 0.03
PIAS-QS+NC	10.14 <sup>bc</sup> ± 1.11	0.86 <sup>a</sup> ± 0.11	29.3 <sup>a</sup> ± 1.2	11.29 <sup>a</sup> ± 9.60	10.21 <sup>b</sup> ± 7.95	14.10 <sup>ab</sup> ± 8.36	11.75 <sup>ba</sup> ± 7.47	73.49 <sup>ab</sup> ± 16.51	83.34 <sup>cd</sup> ± 9.31	0.82 <sup>a</sup> ± 0.83	0.43 <sup>a</sup> ± 0.23
PIAS-QLS	9.44 <sup>bc</sup> ± 2.96	0.35 <sup>a</sup> ± 0.05	35.0 <sup>a</sup> ± 2.9	3.79 <sup>a</sup> ± 3.77	2.69 <sup>ab</sup> ± 1.53	5.44 <sup>a</sup> ± 3.47	3.73 <sup>a</sup> ± 1.36	59.67 <sup>ab</sup> ± 21.95	68.01 <sup>c</sup> ± 12.97	0.17 <sup>a</sup> ± 0.23	0.16 <sup>a</sup> ± 0.08

**Notes:** Olf – initial organic horizon; Ai – initial organic – mineral horizon at 0–8 cm deep; C – parent rock horizon, mean values for 8–50 and 50–110 cm layers cm deep; 1.64<sup>a</sup> ± 0.06 - sample mean and standard deviation (n=4, for BD n=3 for each horizon), for coarse fragment range of % content in volume of soil; site and substrate variants abbreviations – see description in the Table 1; Means of soil-substrate features in horizons with the same letter are not significantly different at p=0.05 by Tukey test.

**Table 5.** Values of the sub-indices of mine soil quality index (MSQI) calculated on the basis of mine soil characteristics.

Mine sites and substrate	CFr %	SFS <sup>1</sup>	CIFS	Is	Isi	Icl	ECS	APS	Ina	IP	C <sub>org</sub> -to-N <sub>t</sub>	Iba	H <sup>+</sup> S	Iac
		Mg·ha <sup>-1</sup> ·110·cm <sup>-1</sup>					Mg·ha <sup>-1</sup> ·110·cm <sup>-1</sup>						kg·ha <sup>-1</sup> ·110·cm <sup>-1</sup>	
BEL-QL	0	4827 <sup>±</sup> 1094	771 ± 87	0.00	0.45	0.15	99.2 ± 13.4	0.2890 ± 0.2128	1.00	1.00	82.8 ± 3.8	0.1	0.0013 ± 0.0005	0.30
BEL-NS	0	2418 ± 1145	982 ± 397	0.00	0.40	0.20	10.3 ± 3.0	0.4800 ± 0.1600	0.45	1.00	83.6 ± 5.7	0.1	27.1510 ± 40.8169	0.50
SMOL-CF	80	3994 ± 111	2775 ± 312	0.30	0.40	0.40	29.3 ± 7.6	0.0235 ± 0.0230	0.75	0.45	31.5 ± 2.6	0.9	13.8250 ± 13.4441	0.20
SMOL-NCF	80	3717 ± 239	2563 ± 172	0.30	0.40	0.30	9.1 ± 4.0	0.0025 ± 0.0038	0.45	0.30	31.5 ± 2.6	0.9	43.5250 ± 17.9632	0.20
SCZ-QLS	0	1952 ± 700	891 ± 183	0.00	0.35	0.15	8.2 ± 1.2	0.0182 ± 0.0040	0.30	0.60	41.0 ± 5.1	0.5	1.0450 ± 0.6087	1.00
SCZ-QS	0	343 ± 115	263 ± 44	0.00	0.10	0.10	2.8 ± 1.0	0.0213 ± 0.0074	0.15	0.45	42.9 ± 5.1	0.5	0.3388 ± 0.3909	1.00
PIAS-QS+NC	5	1172 ± 706	1001 ± 410	0.00	0.30	0.20	27.4 ± 21.2	0.0657 ± 0.0367	0.75	0.45	29.3 ± 1.3	0.9	0.0908 ± 0.1510	0.60
PIAS-QLS	2	387 ± 102	556 ± 90	0.00	0.10	0.10	8.3 ± 2.4	0.0302 ± 0.0125	0.30	0.45	35.0 ± 2.8	0.9	0.2183 ± 0.2578	0.60

<sup>1</sup> SFS - Silt Sized (0.05–0.002 mm) Fraction Stock; CIFS - Clay Sized (<0.002 mm) Fraction Stock; CFr - Coarse Fragments (>2mm); ECS - Exchangeable Cations Form Stock; APS - Available Phosphorus Stock; C<sub>org</sub>-to-N<sub>i</sub> – organic Carbon to total Nitrogen ratio; H<sup>+</sup>S - Hydrogen (H<sup>+</sup>) Stock;

<sup>2</sup> Values of transformed soil characteristics for site and substrate variants are mean with standard deviation (n=4).

## Discussion

As one can see from the above characteristics, comparison of soil quality using particle soil properties is difficult. It is an extremely important to use soil quality indices to make objective comparisons of mine soils developed on varied parent rock mate-

rial and at different post-mining facilities such as external spoil heaps (in sulphur, lignite and hard coal mining) and sand open castpits. Deposits that constitute parent rock in soils on post-mining sites are formed from Quaternary, Neogene and Carboniferous deposits with different physical and chemical features. When numerically assessing various features of transformed soils into sub-indices, what was taken into account was the scale of variability range of these features in the analysed data set.

What was also taken into account were the requirements and ecological properties of the tested species, the Scots pine (*Pinus sylvestris* L.), which dominates the afforested post-mining sites in this part of Europe. The species' wide ecological amplitude, its pioneering in ecological succession and good adaptation potential for difficult habitat conditions (Farjon 2005) are the reasons for its widespread use in afforestation of post-mining sites (Knoche 2005; Baumann et al. 2006; Pietrzykowski 2010; Pietrzykowski and Socha 2011).

Soil texture is one of the most important criteria for the classification of soil deposits. This feature is closely connected and decisive for other soil properties. Among the various fractions, the most important role is played by silt and clay. Silt fraction (0.05–0.002 mm) in sands increases water capacity and capillary conduction, whereas in clays it reduces swelling, viscosity and plasticity. Colloidal clay admixture increases cohesion and plasticity and reduces percolation and water-permeability. Excessive content of the clay fraction, however, adversely affects the air and water properties of soils and water availability for plants.

When developing the soil quality evaluation scale, the silt index (Isi) was based on the assumption that the larger stock of this fraction is “the better”. When developing the soil quality evaluation scale for the clay index (Icl), increases in the content and stock of the clay fraction was considered favourable only up to a certain limit. It was assumed that it was most beneficial from 3501–4000 Mg·ha<sup>-1</sup>·110·cm<sup>-1</sup>, and over this range the Icl value fell. If the clay content in profile exceeds 8500 Mg·ha<sup>-1</sup>·110·cm<sup>-1</sup> cm (that is if the clay fraction constituted on average over 60 % in bulk density of the investigated soils), the Icl sub-index value will drop to 0.2. The coarse fragment fraction CFr (fragments of rocks, stones, gravel of >2.0 mm in diameter) in RMS decreased the value of soil texture index (Ist). In determining the partial value of the Is, coarse fraction was not calculated in advance, as in the case of silt and clay fractions, but the valuation was made on the basis of the percentage (% in sample volume). If the content of silt and clay fraction was very small and the CFr very high in tipped mine deposits, the Ist value in the valuation of soil texture could not be negative (Ist ≥ 0), and in such cases it is assumed that Ist = 0.0.

Another feature included in the valuation of mine soil was availability of nutrients for plants. This feature obviously has a direct impact on growth and nutrition of the introduced tree stands. Nutrient availability sub-index Ina refers to exchangeable cation form stock (ECS): calcium Ca<sup>2+</sup>, magnesium Mg<sup>2+</sup>, potassium K<sup>+</sup> and sodium Na<sup>+</sup>. The available phosphorus (P<sub>av</sub>) is also included in the group of basic macronutrients which are frequently deficient in mine soils (Heinsdorf 1996; Daniels and Stewart 2000; Pietrzykowski 2010). In natural soils, phosphorus occurs in mineral form and its source is mainly fluoroapatite; in organic form, it is connected with plant and animal remains.

In initial mine soils, little organic matter has accumulated and apart from its natural content in rock, which forms spoil heaps and excavations, some amounts of phosphorus are provided in the form of mineral fertilising. The impact of fertilising tree-stands with phosphate may last from several to about a dozen years (Baule and Fricker 1970; Heinsdorf 1996). The scale for IP

was estimated assuming that the increase of the index value is linear, that is “the more phosphorus, the better for the plants.” In some cases on sulphurous neogene sands (BEL-NS), neutralisation by bog lime improved the IP sub-index values. Bog lime used for neutralization is a rock containing phosphorus bound with organic residue formed in the course of sedimentation in neogene lakes.

Soil acidity expressed by pH is a feature very closely connected with other soil properties. The pH in 1MKCl determination is based on an assumption that hydrogen and aluminium ions go into solution in reaction with neutral salt (KCl), and the obtained value is quite stable in the vegetation season and less dependent on soil humidity, for example. This is of particular importance in the case of mine soils that frequently exhibit significant pH variability in vertical profiles. Forest tree species have different requirements regarding pH for both the optimum range and the tolerated range (ecological amplitude).

The investigated species, the Scots pine, has a wide range of tolerance for pH variation, even within the soil profile (Farjon 2005). In the valuation of an Iac acidity index, it was assumed that the smaller the accumulation, the better, but only to a certain limit and then the Iac index grew, and subsequently, below 1.0 kg H<sup>+</sup> ha<sup>-1</sup> 110 cm<sup>-1</sup>, the Iac index dropped (Table 5). This assumption stems from the fact that most forest species grow in natural conditions in soils that are at least slightly acidic and, in the case of mine soils, both extremely low acidity (e.g. mining drainage) and alkalinity are adverse phenomena.

An important criterion in the evaluation of RMS development in post-mining areas is the extent and dynamics of initial organic horizon formation. One measure of development of these horizons is the accumulation of soil organic Carbon (C<sub>org</sub>) and total nitrogen (N<sub>t</sub>) and the C<sub>org</sub>-to-N<sub>t</sub> ratio (Anderson 1977; Wali and Freeman 1973; Prosser and Roseby 1995; Li and Daniels 1994; Rumpel et al. 1999; Pietrzykowski 2008). The fresh litter horizon (OL) is clearly developed and the raw humus horizon (Of) is at an early development stage and hence the symbol OLf (fresh litter and raw humus horizon).

The C<sub>org</sub>-to-N<sub>t</sub> ratio may be interpreted as an indirect index of changes in the developed soil environment, including the intensity of soil organic matter transformation processes (Janssen 1996). With high C<sub>org</sub>-to-N<sub>t</sub> ratio, the stock of mineralised nitrogen may be used by soil micro-organisms, and consequently the accumulation of nitrogen may be stopped. In the sediments freshly deposited on spoil heaps, the phenomenon of nitrogen deficiency (too high C<sub>org</sub>-to-N<sub>t</sub> ratio) may occur periodically (Wali 1999). In the case of RMS, wide C<sub>org</sub>-to-N<sub>t</sub> ratio is connected with slower decomposition of biomass produced by pioneering plant communities (Schafer and Nielsen 1979).

In the case of initial mine soils, there is however a difficulty in interpreting C<sub>org</sub>-to-N<sub>t</sub> ratio due to the occurrence of origin (“geogenic”) carbon that significantly alters the total balance of carbon and soil nitrogen (Chabbi et al., 2008). And so the proposed MSQI includes the C<sub>org</sub>-to-N<sub>t</sub> ratio in OLf horizon in the Iba partial index, which refers to “biological activity”. From the literature (Farjon 2005) it follows that in habitats suitable for the investigated species (Scots pine), the C<sub>org</sub>-to-N<sub>t</sub> ratio in litter is

on average above 60. Series of data indicate, however, that in optimum habitats and with a good supply of nitrogen, the  $C_{org}$ -to- $N_i$  ratio in the Scots pine may be lower than 30 and vary dynamically with the decomposition of litter. Usually the amount of nitrogen in comparison to organic carbon increases in the course of litter decomposition.

#### MSQI relations with features of vegetation

As mentioned above, validation of soil quality indices and suitability in habitat classification may be done through correlation with plant community features (Warkentin 1995; Burger and Kelting 1999; Schoenholtz et al. 2000). It is well known that many plant species from succession are good indicators of habitat conditions. Detailed studies conducted 50 years ago allowed to calibrate many plant species with reference to habitat conditions and ecological indicator values for Central Europe (Ellenberg first in 1965 and reprinted in Ellenberg 2009) were used successfully. The values of MSQI correlated significantly with ecological indicator values of vascular plants: moisture (M) and fertility (F). Variants on Carboniferous shales (SMOL-CF and SMOL-NCF), where the values of MSQI were higher while soil fertility (F) values were the lowest, had significant impact on the reduction of the correlation coefficient values between MSQI and ecological indicator of F. This indicates that predictions of site conditions based on plant community features in some cases may be lower than the assessment of potential soil quality. In such cases, it will be necessary to better plan potential habitat conditions for the introduced tree stands.

The biomass of plant communities and the rate of production of biomass per unit area are other factors important for soil quality and productivity validation. The quantity and spatial distribution of biomass layers and plant constituents is of crucial significance in describing ecosystem productivity (Krebs, 1994). However, the plant biomass of the undergrowth is important from a nutritional viewpoint for reclaimed post-mining site stand stability (Hüttl and Weber, 2001; Knoche et al. 2002; Pietrzykowski and Socha 2011).

Tree stand features, such as biomass and growth parameters (mean diameter and height), on the investigated sites may be more significantly altered by age and forest management operations such as thinning directly affecting the density and competitiveness of trees. Thus, as mentioned in method description (see Section 2), the correlations with these parameters were not considered. The values of MSQI correlated significantly with aboveground biomass of forest floor species. What follows is that MSQI well describes the growth conditions of vegetation that appears by way of natural succession under the canopy of the introduced tree stands.

#### Proposal of final habitat classification and recommendation for species composition

Based on the results of Tukey's HSD test, homogeneous subsets in terms of index values MSQI were distinguished (Table 6 and 7). Mean MSQI values for three homogenous subsets (with low,

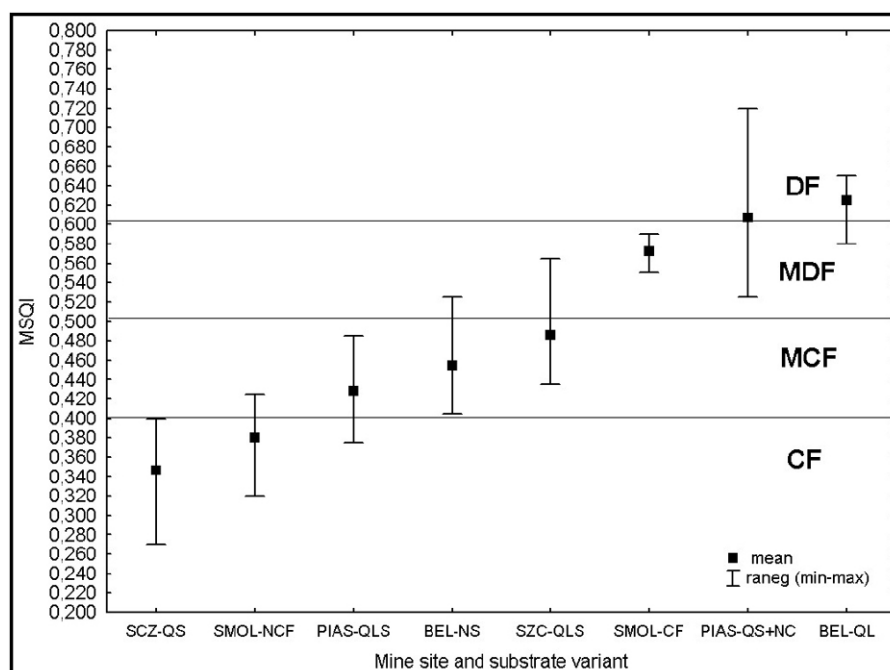
medium, and high MSQI values) were used to determine the range of MSQI values for the grid with site classification (Table 7 and Fig. 2). Based on this grid, the investigated soils developing on different types of rock overburden may be grouped from the poorest to the most fertile soils. Thus, the poorest habitats were found on the Szczakowa sand pit on quaternary sands (SCZ-QS) (MSQI = 0.270), whereas the most fertile ones were found on Piaseczno spoil heap on quaternary sandy loams mixed with neogene clays (PIAS-QS+NC) (MSQI = 0.720) (Fig. 2).

Eventually, the following predicted habitats were classified for the MSQI value ranges: below 0.403 – Coniferous Forests (CF); from 0.404 to 0.505 – Mixed Coniferous Forests (MCF); from 0.506 to 0.602 – Mixed Deciduous Forest (MDF); above 0.602 – Deciduous Forests (DF). It must be noted however that the MSQI ranges for some soils overlapped within the groups. This was due to significant micro-habitat variability and mosaic-like character of sediments that form post-mining sites. In such cases, transition units (e.g., CF/MCF) may additionally be distinguished.

For individual groups of habitat classes distinguished according to similarity in substrates (parent rock), optimal species composition for afforestation and conversion of pine monocultures would be recommended.

For the poorest habitats of coniferous forest (CF) on quaternary sands (e.g., Szczakowa sand pit SCZ-QS) and carboniferous deposits on unfertilized fragments of spoil heaps (Smolnica SMOL-NCF), the Scots pine should be still the main afforestation species in the next generation of tree stands. For mixed coniferous forest sites (MCF) on quaternary loamy sands (on Piaseczno spoil heap PIAS-QLS) and neogene sands (on Belchatów spoil heap BEL-NS) the dominant species should again be the Scots pine, but the addition deciduous trees (e.g., common birch and some sessile oak) is recommended. For transitional habitats, from mixed coniferous to mixed deciduous forest sites (MCF/MDF) classified on quaternary loamy sands (on Szczakowa sand quarry SZC-QLS), the dominant species in the next generation should be the Scots pine, but the introduction of more deciduous trees (e.g. sessile oak) is strongly recommended.

Mixed deciduous forest sites classified on carboniferous deposits of fertilized fragments of a spoil heap (Smolnica SMOL-CF), the conversion of pine monoculture is recommended. The main species on these sites should be deciduous trees (sessile oak with some other deciduous species, e.g., hornbeam, linden, common maple) and only a small percentage of the Scots pine. Transitional habitats, from mixed deciduous to deciduous forest sites (MDF/DF) were classified on a mix of quaternary sands with neogene clays (on Piaseczno sulphur mine spoil heap PIAS-QS+NC). The main species on these sites should be deciduous trees as well (e.g., sessile oak with admixture of hornbeam, linden, common maple) and a very small percentage of the Scots pine.



**Fig. 2.** A grid of predicted groups of forest habitat units for the study sites and substrate (parent rock) variants, based on the range of MSQI: CF - poorest habitats of coniferous forests; MCF - mixed coniferous forest; MDF - mixed deciduous forest; DF - deciduous forest.

**Table 6.** The result of Tukey's HSD (honestly significant difference) test on the significance of mean MSQI (Mine Soil Quality Index) values for soil substrate variants

Mine sites and substrate variant symbol	BEL-QL	BEL-NS	SMOL-CF	SMOL-NCF	SCZ-QLS	SCZ-QS	PIAS-QS+NC	PIAS-QLS
	M =0.625	M =0.455	M =0.573	M =0.380	M =0.486	M =0.346	M =0.608	M =0.429
BEL-QL		<b>0.003730</b>	0.861012	<b>0.000168</b>	<b>0.025044</b>	<b>0.000149</b>	0.999761	<b>0.000793</b>
BEL-NS	<b>0.003730<sup>1</sup></b>		0.083236	0.526889	0.990454	0.131052	<b>0.010948</b>	0.996684
SMOL-CF	0.861012	0.083236		<b>0.000974</b>	0.357413	<b>0.000229</b>	0.981651	<b>0.018603</b>
SMOL-NCF	<b>0.000168</b>	0.526889	<b>0.000974</b>		0.148320	0.985062	<b>0.000222</b>	0.899769
SCZ-QLS	<b>0.025044</b>	0.990454	0.357413	0.148320		<b>0.023257</b>	0.067971	0.798833
SCZ-QS	<b>0.000149</b>	0.131052	<b>0.000229</b>	0.985062	<b>0.023257</b>		<b>0.000154</b>	0.410692
PIAS-QS+NC	0.999761	<b>0.010948</b>	0.981651	<b>0.000222</b>	0.067971	<b>0.000154</b>		<b>0.002193</b>
PIAS-QLS	<b>0.000793</b>	0.996684	<b>0.018603</b>	0.899769	0.798833	0.410692	<b>0.002193</b>	

<sup>1</sup> **0.007494** - marked differences by bold lettering are significant at  $p=0.05$ ; M – mean of MSQI for mine soil and substrate variant.

**Table 7.** Homogeneous subsets of soil-substrate variants in terms of MSQI values based on Tukey's HSD test.

Mine site and substrate variants	MSQI (Mean for variant)	Homogeneous subsets				
		1	2	3	4	5
SCZ-QS	0.346	****				
SMOL-NCF	0.380	****	****			
PIAS-QLS	0.429	****	****			
BEL-NS	0.455	****	****	****		
SCZ-QLS	0.486		****	****	****	
SMOL-CF	0.573			****	****	****
PIAS-QS+NC	0.608				****	****
BEL-QL	0.625					****
mean MSQI for homogenous subsets		<b>0.403<sup>1</sup></b>	0.438	<b>0.505</b>	0.555	<b>0.602</b>

<sup>1</sup> **0.403**- marked mean values by bold lettering for homogenous were subsets used as the ranges for predicted units in forest habitat classification

The most fertile habitats of deciduous forest sites (DF) were classified mostly on Quaternary loam (on ‘Belchatów’ spoil heap BEL-QL) (Table 6). On these deposits the conversion of pine monoculture and afforestation with hard wood species is strongly recommended.

## Conclusions

Reclaimed mining soils developing on post-mining sites are made up of very diverse lithological deposits that exhibit considerable variability. The main factor that affected the variability of MSQI for quaternary and neogene soils (BEL-QL, BEL-NS, SCZ-QLS and SCZ-QS PIAS-QS+NC and PIAS-QLS) was soil texture, which resulted in the value of soil texture index (Ist). Moreover, in the case of soils developed on shales and Carboniferous deposits of Smolnica spoil heap (SMOL-CF and SMOL-NCF), the features that also had an impact were fertility and the resulting sub-indices, including nutrient availability index, Ina, and phosphorus availability index IP.

On this basis, it may be concluded that, with little lithological diversification of sediments on the Smolnica spoil heap, the impact of mineral fertilization was highlighted. The analysis and habitat classification results lead to the conclusion that prediction of plant habitat based solely on lithology and genesis of sediments made of parent rock, in the case of developing mine soils, provides results that are too general. Often the predicted potential fertility of weathering rock overburden based on an analogy with the parent rocks of natural soils, (e.g., shale, and sandstone) may be erroneously interpreted and ultimately give overestimated final results of habitat classification. The conducted habitat classification, especially the examples provided, show that the developed MSQI index is universal and can objectively assess the quality of mine soils in contrast to assessments based solely on soil properties that are typically highly variable.

Moreover, the reliability of the developed MSQI index is confirmed by statistically significant correlations with the tested features of plant communities from succession (ecological indicator values and plant biomass). This indicates the accuracy of the selected components of soil quality assessment included in MSQI and determines fertility of the soils and ability to meet nutritional requirements of plants. As a result of the habitat classification and an indication of the trend that habitats will follow in the process of becoming similar to natural forest habitats, the MSQI index can be useful in designing species composition and pine monoculture transformation in the next generation of “new forests” on mining sites. The MSQI can be applied to describe the variability of mine soils and to classify habitats developed on mine overburden deposits, similar to the investigated substrates, which are dominant in this part of Europe.

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## References

- Anderson DW. 1977. Early stages of soil formation of glacial till mine spoils in semiarid climate. *Geoderma*, **19**: 11–19.
- Andrews JA, Johnson JE, Torbert JL, Burger JA, Kelting DL. 1998. Minesoil and site properties associated with early height growth of Eastern White Pine. *J Environ Qual*, **27**: 192–199.
- Baule H, Fricker C. 1970. *The fertilizer treatment of forest trees*. Munchen, Germany: BLV-Verlagsges, p.259.
- Baumann K, Rumpelt A, Schneider BU, Marschner P, Hüttel RF. 2006. Seedling biomass and element content of *Pinus sylvestris* and *Pinus nigra* grown in sandy substrates with lignite. *Geoderma*, **136**: 573–578.
- Brozek S, Lasota J, Zwydak M, Wanic T, Gruba P, Błońska E. 2011. Application of the trophic soil index (SIG) in the diagnosis of forest site types. *Soil Sci Annual*, **62**(4): 133–149. (In Polish, English Summary)
- Buczko U, Bens O, Fischer H, Hüttel RF. 2002. Water repellency in sandy luvisols under different forest transformation stages in Northeast-Germany. *Geoderma*, **109**: 1–18.
- Burger JA, Johnson JE, Andrews JA., Torbert JL. 1994. Measuring mine soil productivity for forests. In: *International Land Reclamation and Mine Drainage Conference on Reclamation and Revegetation*. USDO, Bureau of Mines, Special Publication, SP 06C-94. p. 48–56.
- Burger JA, Kelting DL. 1998. *Soil quality monitoring for assessing sustainable forest management*. In: M.B. Adams, K. Ramakrishna, E.A. Davidson (eds.) *The Contribution of Soil Science to the Development and Implementation of Criteria and Indicators of Sustainable Forest Management*. *Soil Sci Soc Am, Special Publication*, **53**: 17–52.
- Burger JA, Kelting DL. 1999. Using soil quality indicators to assess forest stand management. *For Ecol Manage*, **122**: 155–166.
- Chabbi A, Sebilo M, Rumpel C, Schaaf W, Mariotti A. 2008. Origin of Nitrogen in reforested lignite-rich mine soils revealed By Stable Isotope Analysis. *Environ Sci Technol*, **42**: 2787–2792.
- Daniels WL, Genthner MH, Hodges RL. 1992. Soil development in sandy tailings derived from mineral sands mining in Florida. In: *Proceedings, National Meeting of the American Society for Surface Mining and Reclamation*. Duluth MN, 14–18 June 1992. Lexington, KY: ASMR, pp. 37–47.
- Daniels WL, Stewart BR. 2000. Reclamation of Appalachian coal refuse disposal areas. In: R. I. Barnhisel, R.G. Darmody, W. Lee Daniels (eds.), J. Bartels (Manag. ed.), *Reclamation of drastically disturbed lands*. Agron. Monogr. 41. Madison, WI: ASA, CSSA, SSSA, p. 433–459.

- De Vos B, Van Meirvenne M, Quataert P, Deckers J, Muys B. 2005. Predictive quality of pedotransfer functions for estimating bulk density of forest soils. *Soils, Soil Sci Am J*, **69**: 500–510.
- Doran JW, Parkin TB. 1996. Quantitative indicators of soil quality: a minimum data set. In: J.W. Doran, A.J. Jones (eds.), *Methods for Assessing Soil Quality. Soil Sci Soc Am Special Publication*, **49**: 25–37.
- Dzwonko Z. 2001. Assessment of light and soil conditions in ancient and recent woodlands by Ellenberg indicator values. *J App Ecol*, **38**(5): 942–951.
- Ellenberg, H. 2009. *Vegetation Ecology of Central Europe*. Cambridge: Cambridge University Press. p. 756.
- Farjon A. 2005. *Pines: Drawings and Descriptions of the Genus Pinus*. 2nd rev. ed. Netherlands: Brill Academic Publishers, p. 236.
- Fischer H, Bens O, Hüttel RF. 2002. Changes in humus form, humus stocks and soil organic matter distribution caused by forest transformation in the northeastern lowlands of Germany. *Forstwiss Centralblatt*, **121**: 322–334.
- Gale MR, Grigal DF, Harding RB. 1991. Soil productivity index: predictions of site quality for white spruce plantations. *Soil Sci Soc Am J*, **55**: 1701–1708.
- Harris RF, Karlen DL, Mulla DJ. 1996. A conceptual framework for assessment and management of soil quality and health. In: J.W. Doran, A.J. Jones (eds.), *Methods for Assessing Soil Quality. Soil Sci Soc Am Special Publication*, **49**: 61–82.
- Heinsdorf D. 1996. Development of forest stands in the Lusatian Lignite Mining District after mineral fertilization adapted to site and tree species. *Water, Air, Soil Pollut*, **91**: 33–42.
- Henderson GS. 1995. Soil organic matter: a link between forest management and productivity. In: W.W. McFee, J.M. Kelly (eds.), *Proceedings of the 8th North American Forest Soils Conference on Carbon Forms and Function in Forest Soils*. Madison, WI: Soil Sci. Am, pp. 419–435.
- Hüttel RF, Weber E. 2001. Forest ecosystem development in post-mining landscapes, a case study of the Lusatian lignite district. *Naturwissenschaften*, **88**: 322–329.
- Jackson ML. 1958. *Soil chemical analysis*. Verlag: Prentice Hall, Englewood Cliffs, NJ. p. 498.
- Janssen BH. 1996. Nitrogen mineralization in relation to C:N ratio and decomposability of organic materials. *Plant Soil*, **181**: 39–45.
- Katzur J, Haubold-Rosar M. 1996. Amelioration and Reforestation of sulfurous mine soils in Lusatia (Eastern Germany). *Water, Air Soil Pollut*, **91**: 17–32.
- Knoche D. 2005. Effects of stand conversion by thinning and underplanting on water and element fluxes of a pine ecosystem (*P. sylvestris* L.) on lignite mine spoil. *For Ecol Manage*, **212** (1–3): 214–220.
- Knoche D, Embacher A, Katzur J. 2002. Water and element fluxes of red oak ecosystems during stand development on post-mining sites (Lusatian Lignite District). *Water, Air Soil Pollut*, **141**: 219–231.
- Knoepp JD, Coleman DC, Crossley DA, Clark JS. 2000. Biological indices of soil quality: an ecosystem case study of their use. *For Ecol Manage*, **138**: 357–368.
- Krzaklewski W, Pietrzykowski M. 2007. Site classification in post-mining areas reclaimed for forest use with special focus on phytosociological-soil method. *Sylwan*, **151**(1): 51–57. (in Polish, English summary)
- Krebs CJ. 1994. *The experimental analysis of distribution and abundance* (4th edition). New York: Harper-Collins College Publishers, p. 801.
- Li RS, Daniels WL. 1994. Nitrogen Accumulation and form over time in young mine soils. *J Environ Qual*, **23**(1): 166–172.
- Mchaina DM. 2001. Environmental planning considerations for the decommissioning, closure and reclamation of a mine site. *International Journal of Surface Mining, Reclamation and Environment*, **15**(3): 163–176.
- Nambiar EKS. 1997. Sustained productivity of forests as a continuing challenge to soil science. *Soil Sci Soc Am J*, **60**: 1629–1642.
- Ostrowska S, Gawlinski Z, Szczubialka Z. 1991. *Procedures for soil and plants analysis*. Warsaw: Institute of Environmental Protection (In Polish), p. 334.
- Pietrzykowski M. 2008. Soil and plant communities development and ecological effectiveness of reclamation on a sand mine cast. *J For Sci*, **54**(12): 567–578.
- Pietrzykowski M. 2010. Scots pine (*Pinus sylvestris* L.) ecosystem macronutrients budget on reclaimed mine sites - stand trees supply and stability. *Nat Sci*, **2**(6): 590–599.
- Pietrzykowski M, Krzaklewski W. 2007. An assessment of energy efficiency in reclamation to forest. *Ecol Eng*, **30**: 341–348.
- Pietrzykowski M, Socha J. 2011. An estimation of Scots pine (*Pinus sylvestris* L.) ecosystem productivity on reclaimed post-mining sites in Poland (Central Europe) with using of allometric equations. *Ecol Eng*, **37**: 381–386.
- Powers RF, Tiarks AE, Boyle JR. 1998. Assessing soil quality: practicable standards for sustainable forest productivity in the United States. In: M.B. Adams, K. Ramakrishna, Davidson, E.A. (eds.), *The Contribution of Soil Science to the Development and Implementation of Criteria and Indicators of Sustainable Forest Management. Soil Sci Soc Am Special Publication*, **53**: 53–80.
- Prosser IP, Roseby SJ. 1995. A chronosequence of rapid leaching of mixed podzol soil materials following sand mining. *Geoderma*, **64**: 297–308.
- Reganold JP, Palmer AS. 1995. Significance of gravimetric versus volumetric measurements of soil quality under biodynamic, conventional, and continuous grass management. *J Soil Water Conserv*, **50** (3): 298–305.
- Rumpel C, Kögel-Knabner I, Hüttel RF. 1999. Organic matter composition and degree of humification on lignite-rich mine soils under a chronosequence of pine. *Plant and Soil*, **213**: 161–168.
- Schafer WM, Nielsen GA. 1979. Soil development and plant succession on 1- to 50-year old strip mine spoils in southeastern Montana. In: M.K. Wali (ed.), *Ecology and Coal Resources Development. Vol. 2*. New York, NY, USA: Pergamon Press, pp. 541–649.
- Schoenholtz SH, Van Miegroet H, Burger JA. 2000. A review of chemical and physical properties as indicators of forest soil quality: challenges and opportunities. *For Ecol Manage*, **138**: 335–356.
- StatSoft, Inc. 2008. STATISTICA (data analysis software system), version 8.1.
- Wali MK. 1999. Ecological succession and the rehabilitation of disturbed terrestrial ecosystems. *Plant Soil*, **213**: 195–220.
- Wali MK, Freeman PG. 1973. Ecology of some mined areas in North Dakota. In: M.K. Wali (ed.), *Some environmental aspects of strip mining in North Dakota*. Education Series 5, Grand Forks, North Dakota Geological Survey. pp. 25–47.
- Warkentin BP. 1995. The changing concept of soil quality. *J Soil Water Conserv*, **50**: 226–228.
- Wikum DA, Shanholtzer GF. 1978. Application of the Braun-Blanquet cover-abundance scale for vegetation analysis in land development studies. *Environ Manage*, **2**(4): 323–329.
- Zarzycki K, Trzecińska-Tacik H, Różański W, Szelaż Z, Wołek J, Korzeniak U. 2002. Ecological indicator values of vascular plants of Poland. In: Z. Mirek (ed.), *Biodiversity of Poland*, W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków. p. 184.